

Experimental Research and Performance Analysis of a Solar-Powered Air-conditioning System in a Green Building

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Abstract: Based on the green building of the Shanghai Institute of Architectural Science, a solar-powered adsorption air-conditioning system was designed. The operational performance under a typical operating mode in summer was studied, which includes temperature variations of solar collector arrays, heat storage tank and adsorption chillers as well as refrigerating output variations of the system. Experimental results show that adsorption chillers have the advantages of low driving temperature, stability and long working time with high efficiency. Under representative working conditions in summer, the average refrigerating output of solar powered air-conditioning system is 15.31kW during operation of 8 hours; moreover, the maximum attains 20kW. Correspondingly, the average system COP is 0.35, and the average solar COP is 0.15. The solar fraction in summer is concluded to be 71.73%. In addition, the variations of solar-powered air-conditioning system performance with ambient parameters (solar radiant intensity and ambient temperature) and operating parameters (temperatures and flow rates) are analyzed.

Key words: solar energy; adsorption chiller; experiment; performance analysis

1. INTRODUCTION

Currently, three environmental problems are internationally known; these are the acid precipitation, the stratospheric ozone depletion, and the global climate change^[1]. The construction and operation of buildings contributes to these environmental loads. Real

progress in environmentally conscious building is more likely to occur via a process of incremental improvements in design method. Ecological considerations have yet to become an integral part of the design process. To succeed architects must be addressed in the same way that the choice of structure and the servicing of a building are universal issues to be resolved^[2].

The concept of green building consequently came into being and stirred extensive interest among the building and energy researches all over the world. Green buildings are examples of applied ecology, where designers understand the constitution, organization, and structure of ecosystems, and the impacts of architecture are considered from an environmental perspective. By utilizing the concepts, methods, and language of ecology, designers can create architecture that intentionally engages the natural system of a site^[3]. As for energy consumption of green buildings, it is highly suggested to reduce fossil fuel by making use of renewable energy, such as solar energy, wind energy and geothermic energy. Being abundant and clean, solar energy is receiving much attention in green building energy system. Generally, the newer green buildings combine several of solar technologies. They may be both energy efficient, solar heated and cooled, and PV powered, i.e. they are simply “solar buildings”^[4].

The major component of any solar system is the solar collector which absorbs incoming solar radiation, converts it into heat, and transforms this heat to a fluid flowing through the collector. Solar collectors have been used in a variety of

applications including solar hot-water supplying, solar space heating and cooling.

Solar cooling of buildings is an attractive idea as the cooling loads and availability of solar radiation are in phase. Additionally, the combination of solar cooling and heating greatly improves the use factors of collectors compared to heating alone. Solar cooling can be accomplished by using either a thermal energy source supplied from a solar collector or electricity supplied from photovoltaics. Photovoltaic cooling, although uses standard refrigeration equipment which is an advantage, has not achieved widespread use because of the low efficiency and high cost of the photovoltaic cells^[1].

Therefore, the majority of solar-powered air-conditioning systems at present are solar sorption and solar-related systems based on solar thermal utilization. In most of the solar cooling systems, hot water driven single-stage lithium bromide absorption chillers are commonly used. Evacuated tubes or other high-grade solar collectors are adopted to provide a hot water temperature of 88-90 °C as a heat source to drive the chiller^[5]. Although a large potential market exists for this technology, existing solar cooling systems are not competitive with electricity-driven or gas-fired air-conditioning systems. The major problems facing solar absorption cooling systems are its high initial cost, low system performance, and solar energy usage for only a short period during 1-day operation.

Another potential solar-powered air-conditioning system is solar adsorption cooling system. Adsorption cooling is the other group of sorption air conditioners that utilizes an agent (the adsorbent) to adsorb the moisture from the air (or dry any other gas or liquid) and then uses the evaporative cooling effect to produce cooling. Solar energy can be used to regenerate the drying agent. Solid adsorbents include silica gels, zeolites, synthetic zeolites, activated aluminas, carbons and synthetic polymers. Liquid adsorbents can be water, triethylene glycol solutions of lithium

chloride and lithium bromide solutions. Wang suggested that for the minitype solar air-conditioning system, solar adsorption cooling system maybe a better chance^[6]. Up to now, the solar-powered adsorption systems have mostly been intermittent and used only for ice making application. For applications such as air conditioning, when the chilled water temperature requirement is only around 6-8°C, two or more adsorption beds can be used to produce a cooling effect continuously. Li et al. established a lumped parameter model to investigate the performance of a solar powered air conditioning system driven by simple flat plate solar collectors^[7]. As for working pairs, Dieng et al. described that compared with adsorption systems that require heat sources with temperatures above 100°C (zeolite-water systems, activated carbon-methanol systems) and conventional compressor chillers, a silica gel / water adsorption refrigerator uses waste heat at below 100°C, which would be suitable for a wider range of solar thermal collector types^[8].

In this paper, a solar-powered adsorption air-conditioning system designed for the green building of Shanghai Institute of Architectural Science was introduced. The operation performance under typical operating mode in summer was studied. Besides, the variations of the system performance with ambient parameters and operating parameters were analyzed.

2. EXPERIMENTAL SET-UP

A solar-powered air-conditioning system was designed and set up for building area of 460 m² to meet the sensible cooling load of 15 kW in summer. Being the power of solar-powered air-conditioning system, 150 m² solar collectors were installed on the roof of the green building, wherein U-type evacuated tubular solar collectors with CPC of area 90 m² were placed on the west side, and the other 60 m² heat pipe evacuated tubular solar collectors on the east side, as shown in Fig.1. Except for solar collector arrays, the solar-powered air-conditioning system is mainly

composed of two silica gel-water adsorption chillers, a cooling tower, fan coils inside air-conditioning rooms and four circulating pumps for solar collectors (Pump 1), hot water (Pump 2), cooling water (Pump 3) and chilled water (Pump 4), respectively. Besides, a heat storage water tank of 2.5 m^3 in volume was employed to collect solar heat, thereby providing hot water for the air-conditioning system. All components were connected by tubes and valves to form the whole flow diagram, as shown in Fig.2.



Fig.1 Arrangement of solar collector array and green building

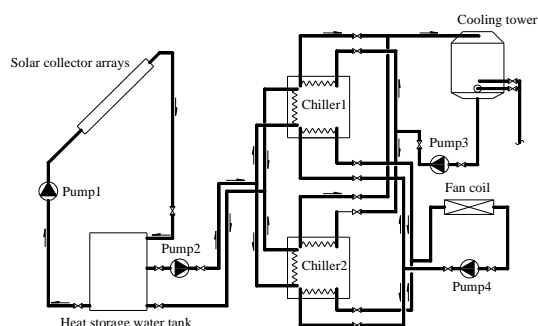


Fig.2 Flow diagram of solar-powered air-conditioning system

The working principle of the system is as follows. The two silica gel-water adsorption chillers are driven by solar hot water. Silica gel adsorbs water vapor, so the water continuously evaporates to produce cooling, and the heat produced due to the adsorption of silica gel is removed by cooling water; when the adsorption comes to its end, the silica gel is heated by hot water to be desorbed and regenerated, and the water vapor expelled from adsorbent is condensed by cooling water. The two chillers work

alternatively, so cooling is produced continuously.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Operation Performance under Typical Operating Mode in Summer

Experimental results under typical weather condition with daily solar radiation of 20.36 MJ/m^2 and average ambient temperature of 31.66°C were chosen to analyze the performance of solar-powered air-conditioning system.

Fig.3 and Fig.4 show the variations of inlet and outlet water temperature for heat pipe solar collector array and U-type evacuated tubular solar collector array, respectively, where point 1 and point 2 represent automatic start of solar collecting circulation, point 3 however signifies automatic stop of solar collecting circulation. It is seen that the water temperatures of inlet and outlet of solar collector arrays, initially, go up with the increase of solar radiant intensity, and approach peak values until 12:00 or so, and then fall off with the decrease of solar radiant intensity. The daily average solar collecting efficiency for heat pipe solar collector array is 36.25%, and 41.79% for U-type evacuated tubular solar collector array.

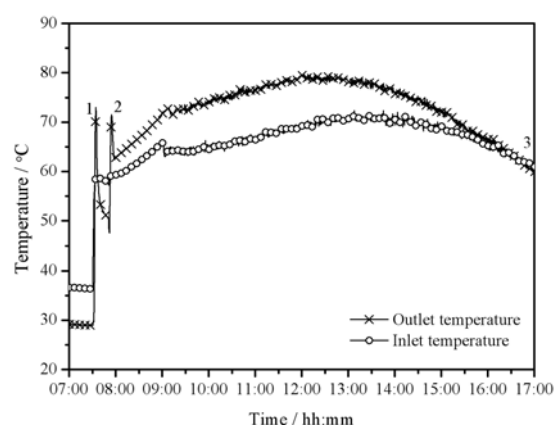


Fig.3 Variations of inlet and outlet water temperature of heat pipe solar collector array

Fig.5 shows the variations of temperatures inside the heat storage water tank during operation of air-conditioning system, where point 4 represents the start of adsorption chillers. From

point 1 to point 4, none but solar collecting circulation is in operation, which leads to the increase of water temperature without thermal stratification. However, when the adsorption chillers turn on, obvious thermal stratification can be seen. The temperature of the middle is a little higher than that of the bottom by 0.38 °C. The daily average temperature of the top is higher than that of the middle by 3.01 °C, and attains to 70.89 °C. At 13:00 or so, the temperature of the heat storage water tank approaches maximal value. From then on, it descends by degrees owing to the decrease of solar radiant intensity. Besides, thermal stratification becomes weaker. Since the hot water at the top is supplied to adsorption chillers, so the thermal stratification helps to improve performance of the system.

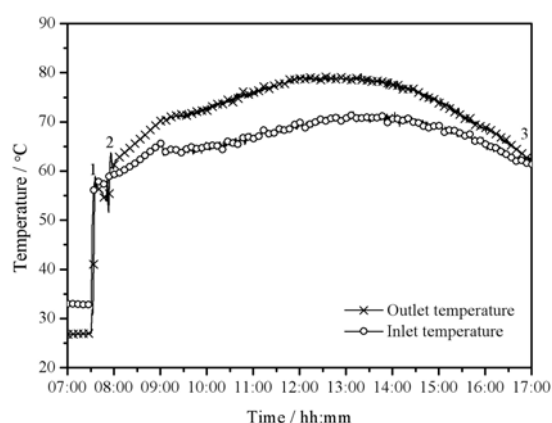


Fig.4 Variations of inlet and outlet water temperature of U-type pipe solar collector array

Fig.6 shows the variations of inlet and outlet temperatures of hot water, cooling water and chilled water during system operation, where $T_{hw,in}$ and $T_{hw,o}$ are inlet and outlet temperature of hot water, respectively, correspondingly, $T_{co,in}$ and $T_{co,o}$ for cooling water, and $T_{chill,in}$ and $T_{chill,o}$ for chilled water. During operation, the average hot water temperature is 70.24 °C and the maximum value reaches 75.58 °C at 13:00. Besides, the average outlet temperature of chilled water is 18.48 °C, which is suitable for dry operating mode of the air-conditioning system. Also can be seen is that the chilled water temperature difference

between inlet and outlet averages at 3.53 °C

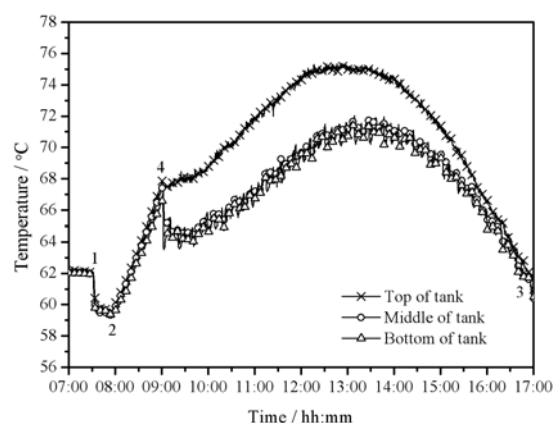


Fig.5 Variations of temperatures inside heat storage water tank during operation of air-conditioning system

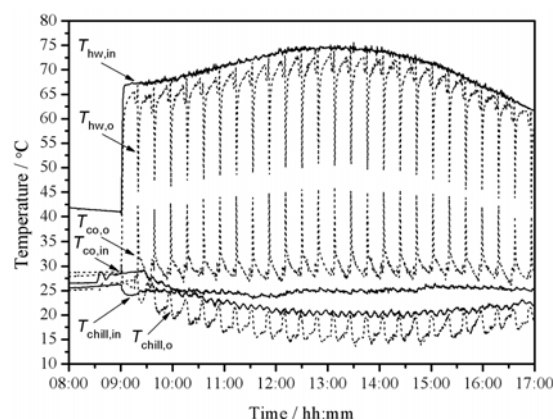


Fig. 6 Variations of inlet and outlet temperatures of hot water, cooling water and chilled water

Fig.7 shows variation of refrigeration capacity. It is seen that the system yields average refrigerating output of 15.31kW during the whole operation, which satisfies design standard. With regard to heat consumption of two adsorption chillers, the average system COP is 0.35, and average solar COP is 0.15 concerning daily solar insolation. Moreover, the maximal refrigerating output exceeds 20 kW. As for solar-powered air-conditioning system, it is significant to reduce power consumption; consequently, electric COP is another important index to evaluate performance of the system. In this system, taking solar collecting pump (P1), hot water pump (P2) and cooling water pump (P3) into account, the whole

power consumption is 1.87 kW, and then the electric COP averages at 8.19 during 8-hour operation, and the maximum exceeds 10.

3.2 Performance Analysis with Ambient Parameters and Operating Parameters

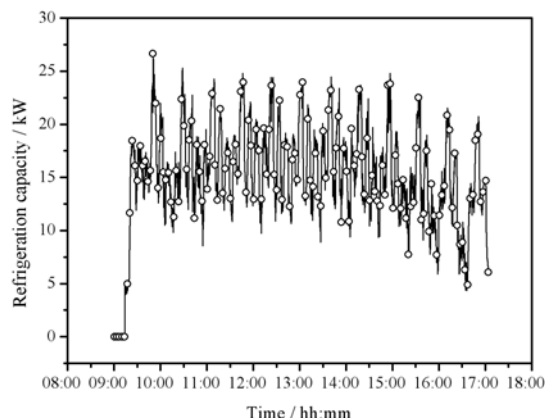


Fig.7 Variations of refrigeration capacity of solar-powered adsorption air-conditioning system

From June to August in 2005, the solar-powered air-conditioning system had continuously run in working hours (9:00~17:00) of the green building. The average refrigerating capacity is concluded to be 10.76 kW. Thus solar fraction for the system in summer attains 71.73% corresponding to the design cooling load.

Based on the available experimental results, variations of main performance indexes of solar-powered air-conditioning system with ambient parameters (solar radiant intensity and ambient temperature) and operating parameters (temperature and flow rate) were analyzed. Fig.8 shows variations of performance indexes of solar-powered adsorption air-conditioning system with daily solar insolation when the ambient temperature is about 30 °C. It is seen that solar collecting efficiency increases with the increase of daily solar insolation, which leads to the augment of solar collecting heat. As a result, the refrigeration capacity subsequently goes up with the increase of daily solar insolation. Also can be found is that solar COP falls off with the increment of daily solar insolation, which indicates that the increase of daily solar insolation

overwhelms that of refrigeration capacity.

Fig.9 shows variations of performance indexes of solar-powered adsorption air-conditioning system with average ambient temperature when the daily solar insolation is about 18 MJ·m⁻². It is seen that all performance indexes including solar collecting efficiency, refrigeration capacity and solar COP slightly go up with the increase of ambient temperature. Therefore, it can be deduced that solar radiant intensity has a more distinct influence on the performance of solar-powered air-conditioning system compared with ambient temperature.

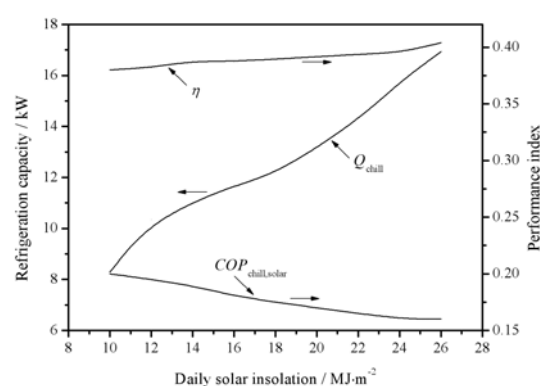


Fig.8 Variations of performance of solar-powered adsorption air-conditioning system with daily solar insolation

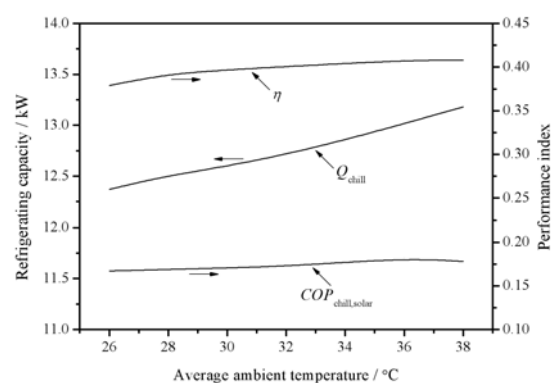


Fig.9 Variations of performance of solar-powered adsorption air-conditioning system with average ambient temperature

Experimental results show that, either hot water or cooling water or chilled water, temperature has more notable influence on the system performance than flow rate under

otherwise similar conditions. Tab.1 lists effects of hot water temperature and flow rate on the performance of the system, where T_a is average

ambient temperature, I is daily solar insolation, V_{hw} , V_{co} , and V_{chill} are flow rate of hot water, cooling water and chilled water, respectively.

Tab.1 Effect of hot water temperature and flowrate on solar-powered air-conditioning system

Date (dd/mm/yy)	T_a ()	I (MJ/m ²)	$T_{hw,in}$ ()	$T_{co,in}$ ()	$T_{chill,in}$ ()	V_{hw} m ³ /h	V_{co} m ³ /h	V_{chill} m ³ /h	Q_{chill} (kW)	$COP_{chill,solar}$
19/06/05	29.89	16.04	60.21	25.56	24.87	2.38	4.55	1.10	8.98	0.11
16/06/05	30.57	16.15	63.83	25.31	20.05	4.62	4.42	1.01	10.01	0.12

Tab.2 Effect of chilled water temperature and flowrate on solar-powered air-conditioning system

Date (dd/mm/yy)	T_a ()	I (MJ/m ²)	$T_{hw,in}$ ()	$T_{co,in}$ ()	$T_{chill,in}$ ()	V_{hw} m ³ /h	V_{co} m ³ /h	V_{chill} m ³ /h	Q_{chill} (kW)	$COP_{chill,solar}$
30/05/05	25.48	19.67	61.08	24.18	16.78	4.60	4.60	3.34	9.92	0.10
05/06/05	25.91	20.13	61.70	24.00	22.29	4.68	4.54	1.10	12.21	0.12

Tab.3 Effect of cooling water temperature and flowrate on solar-powered air-conditioning system

Date (dd/mm/yy)	T_a ()	I (MJ/m ²)	$T_{hw,in}$ ()	$T_{co,in}$ ()	$T_{chill,in}$ ()	V_{hw} m ³ /h	V_{co} m ³ /h	V_{chill} m ³ /h	Q_{chill} (kW)	$COP_{chill,solar}$
08/06/05	27.20	14.55	62.42	24.07	19.19	4.67	2.42	0.97	7.64	0.08
16/06/05	30.03	15.99	62.10	24.92	18.95	4.62	4.46	1.18	10.11	0.12
28/06/05	32.73	15.04	63.90	29.12	20.90	4.72	4.55	1.39	6.75	0.07

It is seen that refrigerating capacity as well as solar COP attains higher value with the increase of hot water temperature and flow rate. Similar trend for chilled water can be seen in Tab.2. However, there is a little difference for cooling water from Tab.3 as the system performance can be improved with lower temperature.

4. CONCLUSIONS

A solar-powered air-conditioning system was designed and constructed for the green building of Shanghai Research Institute of Building Science. The system was in operation from June to August in 2005. Based on the experimental results, the main conclusions can be summed up as following:

(1) Under representative working condition in summer, the average refrigerating output of solar-powered air-conditioning system is 15.31kW during operation of 8 hours; moreover, the maximum exceeds 20kW. Correspondingly, the daily average system COP is 0.35, and average solar COP is 0.15.

(2) The solar fraction of the solar-powered air-conditioning system in summer is concluded to be 71.73%.

(3) It can be deduced that solar radiant intensity has a more distinct influence on the performance of solar-powered air-conditioning system compared with ambient temperature. In addition, either hot water or cooling water or chilled water, temperature has more notable influence on the system performance than flow rate under otherwise similar conditions.

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